REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
12-09-2012	Final Report	March 1, 2009 - November 30, 2011

4. TITLE AND SUBTITLE Connectivity and Resilience in Large-Scale Mobile Wireless Networks	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER FA9550-09-1-0187
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Edmund Yeh	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Yale University New Haven, CT 06520	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR 875 N Randolph St Arlington, VA 22203	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-OSR-VA-TR-2012-1075

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project has supported the analysis and design of large-scale mobile wireless networks for Air Force applications, including information dissemination algorithms for fixed wireless and mobile wireless networks, energy management algorithms for sensor networks, resilience of wireless networks to virus epidemics, network coding capacity of wireless networks, coding for mobile wireless networks, polar coding for multiple-access networks, and the capacity of wireless relay networks. The project has supported the education and research activities of a postdoctoral fellow and a graduate student.

15. SUBJECT TERMS

Sensor networks, network coding, random geometric graphs, wireless networks, network resilience, connectivity, information dissemination, mobile wireless networks, polar codes, wireless relay networks, cascading failure, power networks

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	U	8	Dr Robert Bonneau
					19b. TELEPHONE NUMBER *(Include area code)* 703-588-0664

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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

AFOSR Final Performance and Patent Report

Project Title: Connectivity and Resilience in Large-Scale Mobile Wireless Networks

Award Number: FA9550-09-1-0187

Start Date: March 1, 2009

Program Manager: Dr. Robert Bonneau
AFOSR/RSL
875 N Randolph
Arlington, VA 22203
robert.bonneau@afosr.af.mil
Tel (703) 696-9545

Principal Investigator: Edmund M. Yeh
Associate Professor of Electrical and Computer Engineering
416 Dana Research Center
Northeastern University
Boston, Massachusetts 02115-5000
eyeh@ece.neu.edu
Phone: 617-373-5400
Fax: 617-373-8970

Accomplishments/New Findings:

The main focus of this project is the analysis and design of large-scale mobile wireless networks for high connectivity and netework resilience. Over the duration of the reporting period, we have concentrated on the following research activities:

1. Develop distributed energy management algorithms for sensor networks which enhance energy efficiency while maintaining network connectivity.

2. Characterize connectivity and delay for information dissemination algorithms in fixed wireless networks with fading.

3. Characterize connectivity and delay for information dissemination algorithms in mobile wireless networks.

4. Analyze resilience to dependent and cascading node failures in large-scale wireless networks.

5. Analyze resilience to dependent and cascading link failures in large-scale electrical power networks.

6. Characterize the capacity of large-scale interference-limited wireless networks under network coding.

7. Improve the fundamental throughput-delay tradeoff in mobile wireless networks.

8. Develop low-complexity codes to achieve the capacity of wireless relay networks.

9. Develop polar coding schemes to achieve the capacity of multiple-access channels with low complexity.

Summary:

The following are detailed results for the above research activities:

1. In battery-constrained wireless sensor networks, it is important to employ effective energy management while maintaining some level of network connectivity. Viewing this problem from a percolation-based connectivity perspective, the PI has developed a fully distributed energy management algorithm for large-scale wireless sensor networks. This algorithm allows each sensor to probabilistically schedule its own activity based on its node degree. This mechanism is modelled by a degree-dependent dynamic site percolation process on random geometric graphs. The PI has specified the conditions under which the resulting network is guaranteed to be percolated for all time. The PI has further studied the delay performance of the proposed energy management algorithm by modelling the problem as a degree-dependent first passage percolation process on random geometric graphs.

2. The PI has studied connectivity and transmission latency in wireless networks with unreliable links from a percolation-based perspective. The PI first examined static models, where each link of the network is functional (active) with some probability, independently of all other links, where the probability may depend on the distance between the two nodes. The PI has obtained analytical upper and lower bounds on the critical density for phase transition in this model. The PI then examines dynamic models, where each link is active or inactive according to a Markov on-off process. The PI shows that a phase transition also exists in such dynamic networks, and the critical density for this model is the same as the one for static networks under some mild conditions. Furthermore, due to the dynamic behavior of links, a delay is incurred for any transmission even when propagation delay is ignored. The PI has studied the behavior of this transmission delay and showed that the delay scales linearly with the Euclidean distance between the sender and the receiver when the network is in the subcritical phase, and the delay scales sub-linearly with the distance if the network is in the supercritical phase.

3. In wireless networks, node mobility may be exploited to assist in information dissemination over time. The PI has analyzed the latency for information dissemination in large-scale mobile wireless networks. To study this problem, the PI maps a network of mobile nodes to a network of stationary nodes with dynamic links. The PI then uses results from percolation theory to show that under a constrained i.i.d. mobility model, the scaling behavior of the latency falls into two regimes. When the network is not percolated (subcritical), the latency scales linearly with the initial Euclidean distance between the sender and the receiver; when the network is percolated (supercritical), the latency scales sub-linearly with the distance.

4. The PI has studied the problem of resilience to node failures in large-scale networks modelled by random geometric graphs. Adopting a percolation-based view, the PI investigates the ability of the network to maintain global communication in the face of dependent node failures. The PI examines degree-dependent site percolation processes on random geometric graphs, and obtain the first known analytical conditions for the existence and non-existence, respectively, of a large connected component of operational network nodes after degree-dependent node failures. In electrical power networks or wireless communication and computing networks, cascading failure from power blackouts or virus epidemics may result from a small number of initial node failures triggering global failure events affecting the whole network. Using a simple but descriptive model, the PI shows that the cascading failure problem is equivalent to a degree-dependent percolation process. The PI obtains the first analytical conditions for the occurrence and non-occurrence of cascading failures, respectively, in large-scale networks with geometric constraints.

5. Large-scale power blackouts caused by cascading failure are inflicting enormous socioeconomic costs. The PI has studied the problem of cascading link failures in power networks modelled by random geometric graphs from a percolation-based viewpoint. To reflect the fact that links fail according to the amount of power flow going through them, the PI introduces a model where links fail according to a probability which depends on the number of neighboring links. The PI devises a mapping which maps links in a random geometric graph to nodes in a corresponding dual covering graph. This mapping enables the PI to obtain the first-known analytical conditions on the existence and non-existence of a large component of operational links after degree-dependent link failures. Next, the PI presents a simple but descriptive model for cascading link failure, and uses the degree-dependent link failure results to obtain the first-known analytical conditions on the existence and non-existence of cascading link failures.

6. The PI has studied the network coding capacity for random wireless networks. Previous work on network coding capacity for random wired and wireless networks have focused on the case where the capacities of links in the network are independent. In this work, the PI considers a more realistic model, where wireless networks are modeled by random geometric graphs with interference and noise. In this model, the capacities of links are not independent. By employing coupling and martingale methods, the PI shows that, under mild conditions, the network coding capacity for random wireless networks

still exhibits a concentration behavior around the mean value of the minimum cut. Simulation results confirm our theoretical predictions.

7. The PI has studied the throughput-delay performance tradeoff in large-scale wireless ad hoc networks. It has been shown that the per source-destination pair throughput can be improved from $\Theta(1/\sqrt{n \log n})$ to $\Theta(1)$ if nodes are allowed to move and a 2-hop relay scheme is employed. The price paid for such an improvement on throughput is large delay. Indeed, the delay scaling of the 2-hop relay scheme is $\Theta(\sqrt{n \log n})$ under the random walk mobility model. In this paper, we employ coding techniques to improve the throughput-delay trade-off for mobile wireless networks. For the random walk mobility model, the PI's results improve the delay from $\Theta(\sqrt{n \log n})$ to $\Theta(n)$ by employing Reed-Solomon codes. The PI's new approach maintains the diversity gained by mobility while decreasing the delay.

8. The capacity of multiuser networks has been a long-standing problem in information theory. Recently, Avestimehr et al. have proposed a deterministic network model to approximate wireless networks. For multicast, they have shown that the capacity for the deterministic model is equal to the minimal rank of the incidence matrix of a certain cut between the source and any of the sinks. Their proposed code construction, however, is not guaranteed to be efficient and may potentially involve an infinite block length. The PI has developed an efficient linear code construction for the deterministic wireless multicast relay network model. Unlike several previous coding schemes, the PI does not attempt to find flows in the network. Instead, the new construction maintains an invariant where it is required that at each stage of the code construction, certain sets of codewords are linearly independent.

9. Achieving the fundamental capacity limits of noisy communication channels with low complexity coding schemes has been a major challenge for over 60 years. Recently, a revolutionary coding construction, called Polar coding, has been shown to provably achieve the Shannon capacity of discrete memoryless single-user channels. Whereas a number of practical coding constructions (e.g. Turbo codes and Low Density Parity Check codes) can empirically approach the capacity of single-user communication channels, there is still an absence of good practical coding schemes for multi-user communication networks. In recent work, the PI has invented a polar coding scheme which can achieve some of the optimal transmission rates for multiple-access (uplink) networks. The encoding and decoding complexity of the code is $O(n \log n)$ with n being the block length, and the block error probability is roughly $O(2^{-\sqrt{n}})$. The new coding construction is one of the first low-complexity coding schemes which can provably achieve Shannon capacity in multi-user communication networks.

Personnel:

Faculty: Edmund M. Yeh (Yale)

Postdoctoral Fellow Elona Erez (Yale)

Graduate Student: Yun Xu (Yale); M. Phil. Degree in EE, May 2009.

Publications/Accepted or In Print (partially or fully supported by this project, 2009-present):

1. Zhenning Kong and Edmund M. Yeh, "Correlated and Cascading Node Failures in Random Geometric Networks: A Percolation View." *Proceedings of the IEEE International Conference on Ubiquitous and Future Networks (ICUFN)*, Phuket, Thailand, July 4-6, 2012. Co-authored with graduate student. **Best Paper Award**.

2. Zhenning Kong, Edmund M. Yeh, and Emina Soljanin, "Coding Improves the Throughput-Delay Tradeoff in Mobile Wireless Networks." To appear in *IEEE Transactions on Information Theory*, 2012.

3. Zhenning Kong and Edmund M. Yeh, "Degree-Dependent and Cascading Node Failures in Random Geometric Networks." *Proceedings of IEEE Military Communications Conference (MILCOM)*, Baltimore, MD, November 7-10, 2011.

4. Hongda Xiao and Edmund M. Yeh, "Cascading Link Failure in the Power Grid: A Percolation-Based Analysis." *Proceedings of the IEEE International Workshop on Smart Grid Communications*, June 5, 2011, Kyoto, Japan.

5. Zhenning Kong and Edmund M. Yeh, "Resilience to Degree-dependent and Cascading Node Failures in Random Geometric Networks." *IEEE Transactions on Information Theory*, Vol. 56, No. 11, November 2010, pp. 5533-5546.

6. Elona Erez, Yun Xu, and Edmund M. Yeh, "Coding for the Deterministic Network Model." *Proceedings of the Allerton Conference on Communication, Control, and Computing*. Monticello, IL, September 29-October 1, 2010, pp. 1534-1541.

7. Elona Erez, Yun Xu, and Edmund M. Yeh, "Coding for Deterministic Relay Networks." *Proceedings of the Information Theory and Applications Workshop (ITA)*, San Diego, CA, January 31-February 5, 2010.

8. Eren Sasoglu, Emre Telatar, and Edmund M. Yeh, "Polar Codes for the Two-user Binary-input Multiple-access Channel." *Proceedings of the 2010 IEEE Information Theory Workshop (ITW)*, Cairo, Egypt, January 6-8, 2010, pp. 1-5.

9. Zhenning Kong, Edmund M. Yeh, and Emina Soljanin, "Coding Improves the Throughput-Delay Trade-off in Mobile Wireless Networks." *Proceedings of the International Symposium on Information Theory (ISIT)*, Seoul, Korea, June 28-July 3, 2009, pp. 1784-1788.

10. Zhenning Kong and Edmund M. Yeh, “Wireless Network Resilience to Degree-dependent and Cascading Node Failures.” *Proceedings of the International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, Seoul, Korea, June 23-27, 2009, pp. 1-6.

Interactions/Transitions (partially or fully supported by this project, 2009-present): Other interactions include the following technical presentations:

1. ``Polar Codes for Multiple Access Channels." Technical University of Munich, Germany, June 8, 2012.

2. ``Connectivity and Resilience of Large-scale Wireless Networks: A Percolation View." Graph Exploitation Symposium, Dedham, MA, April 17-18, 2012.

3. ``Polar Codes for Multiple Access Channels," Mathematical and Algorithmic Sciences Research Center, Alcatel-Lucent Bell Laboratories, Murray Hill, NJ, April 11, 2012.

4. ``Polar Codes and Power Blackouts." Department of Electrical Engineering, Columbia University, May 3, 2011.

5. ``Network Science: Information Dissemination, Mobility, and Resilience." Department of Electrical and Computer Engineering, University of Wisconsin at Madison, February 24, 2011.

6. ``Polar Codes and Power Blackouts." Department of Electrical Engineering, University of Southern California, February 14, 2011.

7. ``Network Science: Information Dissemination, Mobility, and Power Blackouts." Department of Electrical Engineering, University of California at Los Angeles, February 10, 2011.

8. ``Polar Codes for Multiple Access Channels." Information Theory and Applications Workshop, University of California at San Diego, February 8, 2011.

9. ``Polar Codes and Power Blackouts." Department of Electrical Engineering, California Institute of Technology, February 2, 2011.

10. ``Network Science: Information Dissemination, Mobility, and Power Blackouts." Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan, November 11, 2010.

11. ``Network Science: Information Dissemination, Mobility, and Power Blackouts." Department of Electrical and Computer Engineering, University of California at San Diego, November 3, 2010.

12. ``Cascading Failure in Power Networks: a Percolation-Based Analysis." DIMACS Workshop on Algorithmic Decision Theory for the Smart Grid, New Brunswick, NJ, October 26, 2010.

13. ``Network Science for Wireless Communication: Information Dissemination, Mobility, and Resilience." University of Massachusetts at Amherst, October 18, 2010.

14. ``Network Science for Wireless Communication: Information Dissemination, Mobility, and Resilience." PARC (Palo Alto Research Center), October 11, 2010.

15. ``Polar Codes for Multiple Access Channels." Department of Information Engineering, Chinese University of Hong Kong, June 9, 2010.

16. ``Wireless Computing Networks: Mobility, Connectivity, and Epidemics." Department of Electrical Engineering, Duke University, Durham, NC, March 22, 2010.

17. ``Network Science for Wireless Communication: Information Spread, Mobility, and Resilience." Mathematical and Algorithmic Sciences Research Center, Alcatel-Lucent Bell Laboratories, Murray Hill, NJ, March 5, 2010.

18. ``Network Science: Power Grids, Wireless Communication, and Epidemics." Department of Electrical Engineering, University of Southern California, February 8, 2010.

19. ``Connectivity, Mobility, and Information Dissemination." Information Theory and Applications Workshop, University of California at San Diego, February 4, 2010.

20. ``Network Science: Information Spread, Epidemics, Mobility and Cascading Failures." Workshop on ``Network Science: New Directions in Control Systems," IEEE Conference on Decision and Control (CDC), Shanghai, China, December 15, 2009.

21. ``Network Science for Wireless Communication: Information Spread, Mobility and Resilience." Wireless Institute, Department of Electrical Engineering, University of Notre Dame, December 10, 2009.

22. ``Network Science: Information Spread, Epidemics, Mobility and Cascading Failures." Department of Electrical Engineering, Columbia University, December 7, 2009.

23. ``Network Science for Wireless Communication: Information Spread, Mobility and Resilience." Department of Electrical Engineering and Computer Science, MIT, December 4, 2009.

24. ``Network Science: Information Spread, Epidemics, Mobility and Cascading Failures." ECE Colloquium, School of Electrical and Computer Engineering, Cornell University, November 17, 2009.

25. ``Network Science for Wireless Communication: Information Spread, Mobility and Resilience." Electrical Engineering Systems Seminar, Department of Electrical Engineering, California Institute of Technology, November 13, 2009.

26. ``Network Science for Wireless Communication: Information Spread, Mobility and Resilience." Information Systems Laboratory Colloquium, Department of Electrical Engineering, Stanford University, November 12, 2009.

27. ``Percolation Theory and Large-scale Wireless Networks: Connectivity and Transmission Delay." Department of Information Technology and Electrical Engineering, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, August 17, 2009.

New Discoveries, Inventions, or Patent Disclosures (2009-present):

None

Honors/Awards (2009-present):

1. Best Paper Award, IEEE International Conference on Ubiquitous and Future Networks (ICUFN), Phuket, Thailand, July 2012.

2. Elected Senior Member of the IEEE, 2012.

3. Humboldt Research Fellowship from Alexander von Humboldt Foundation, 2010.

4. Invited to National Science Foundation Future Internet Architecture Summit, 2009.